

General Aviation Approach and Landing Analysis using Flight Data Records

Tejas Puranik*, Evan Harrison*, Sanggyu Min*,
Hernando Jimenez[†], and Dimitri Mavris[‡]

Georgia Institute of Technology, Atlanta, Georgia, 30332-0150

Ensuring a safe and stabilized approach and landing is one of the important objectives in General Aviation applications. This phase is one of the main phases during which accidents occur. A “nominal” or reference trajectory for General Aviation approach and landing operations is critical for flight instruction and retrospective safety assessments reliant on flight data records captured with on-board systems. While this is a more crisply defined area in commercial aircraft operations, it is not so well-defined in General Aviation. The different aspects that need to be considered in defining a nominal trajectory and provide analyses that can be carried out using flight data records are examined. Various ways of defining this nominal or reference approach trajectory are proposed with the eventual aim of using this in conjunction with energy-based methods and metrics to assess and enhance safety in General Aviation aircraft operations.

I. Introduction

One of the most important objectives among operations in the General Aviation (GA) community is to improve safety across all flight regimes. Loss-of-control (LoC) is one of the largest contributors to fatal aircraft accidents.¹ It is a significant contributor to accidents in all aircraft types, operations, and phases of flight. More specifically the approach and landing phase is identified as one of the key phases in which accidents occur.² Flight data monitoring (FDM) or Flight Operations Quality Assurance (FOQA)³ programs in the general aviation sector aim to improve safety via data collection from on-board recorders and retrospective analysis of flight data records. An assessment of approach and landing operational safety with FDM is realized by segregating the portions of one (or more) flight data records corresponding to these phases of flight, and comparing each data point against aircraft states of interest. Adherence to a nominal approach trajectory, touchdown point on the runway, and touchdown speed are measures of flight quality during approach and landing, respectively, that can be extracted from flight data records.

Conducting a safe and efficient landing is of key importance to operators and air traffic regulators. Such a landing profile is often defined as an optimal approach and landing trajectory based on the consideration of multiple objectives. Several of these objectives include maintaining low noise, the desire to drive down operating costs, minimizing fuel burn, maximizing throughput, and maximizing safety. FDM has proven to be a useful tool in enabling the definition of optimal approach and landing trajectories.

The problem of defining the best or most optimal approach and landing trajectory for an aircraft has been tackled extensively in literature. Most of the prior work has been performed for commercial aircraft application. Noise abatement procedures play a key role in deciding the altitude and velocity profile followed by commercial aircraft.^{4,5,6} A lot of the descent trajectory definition and optimization happens between a much higher altitude (≈ 7000 feet AGL) and ILS interception altitude (500-1000) feet AGL. Some of these approach and landing trajectories are elaborated here. Continuous Descent Approach⁴ consists of an idle-thrust descent following a three degree glide slope. Advanced Continuous Descent Approach (ACDA)⁷ aims to improve upon the deficiencies of CDA due to differences in aircraft performance. The velocity

*Graduate Researcher, Daniel Guggenheim School of Aerospace Engineering, AIAA Student Member

[†]Research Faculty, Daniel Guggenheim School of Aerospace Engineering, AIAA Senior Member

[‡]S.P. Langley NIA Distinguished Regents Professor, Daniel Guggenheim School of Aerospace Engineering, AIAA Fellow

profile in this approach consists of a stepped decrease. Three Degree Decelerating Approach (TDDA)⁴ consists of continuous deceleration at 3 degree glide slope. Free Degree Decelerating Approach (FDDA)⁸ and Vertical Flight-path angle Approach (VFA),⁶ allow for variable glide slopes with different schedules for velocity profiles. Comparatively, little work along these lines has been performed with GA applications in mind. Commercial aircraft aim to arrive at ILS glide slope interception point (≈ 1000 feet Above Ground Level - AGL) in full landing configuration and follow the glide slope from that point. As seen later, there is a lot of variability in GA operations prior to intercepting the glide slope. Therefore, while the objectives of minimizing cost, fuel burn and noise are well defined for commercial aircraft, few explicit objectives of this nature can be found for the GA aircraft category. Possible explanations for this gap in defined objectives include - limited data collection hardware availability on some of the less instrumented GA aircraft, lower operational volume, reduced homogeneity of aircraft operations. Thus, it becomes harder to define some of these complex automated 3-D flight path approaches for GA applications.

Unstabilized approaches are one of the important causes of accidents in GA.² Several rules or guidelines for a safe approach and landing exist. In order to assess the relative safety of an approach and landing, a nominal or reference approach and landing trajectory definition is desirable. A nominal approach trajectory can mean several different things. In the context of enhancing the safety of GA operations - a nominal approach trajectory would be one that has been observed to be safe and feasible to fly either from previous flight records or performance models of the aircraft. This may involve using various rules of thumb or safe practices, statistical data of flight records, certain objectives from the commercial operations or a combination of all of these. Along with providing methods to obtain a reference trajectory, we provide further analyses such as obtaining a distribution of touchdown points, touchdown velocities, and various ways of obtaining the best set of parameters to gain these insights from raw flight data records. In addition, the quantification of safety can be provided using energy-based metrics defined using the aircraft state and/or performance models of the aircraft. Such performance models have been developed in concurrent work for this project.^{9,10} A formal development of the energy-based metrics is addressed in Puranik et al.¹¹

The rest of the paper is organized as follows: Section II contains an outline of the methodology followed. Section III contains the implementation of this methodology and results. Section IV lists the conclusions and potential applications of this work.

II. Proposed Methodology

In this paper, various aspects of the problem of defining a nominal approach trajectory for GA operations are explored. Flight data from training flights on a Cessna C172S are utilized for this purpose. This data contains records from instructional flights and provides information about aircraft state characteristics such as altitude, true airspeed, indicated airspeed, latitude, longitude etc. collected at a 1 second interval. In addition to this, basic runway and airport information is assumed to be known from open source such as Airnav website.¹²

The methodology consists of two key analyses - obtaining the touchdown point and obtaining a nominal profile. The entire process is outlined in Figure 1 which shows the inputs, outputs, and steps involved in each analysis. During analysis, the flight data is typically anchored at a specific event in time and data from all the flights is sampled at a fixed temporal or distance-based intervals from this point. This makes the flight data across a large number of flights comparable to each other. In approach and landing operations (which is the focus of this paper), this is typically the touchdown point. The flight data parameters (including altitude and velocity) can be backtracked from this point at a desired discretization and upto a specific distance. The flight data needs to be smoothed as it contains a lot of noise in all the parameters recorded. Obtaining the touchdown point involves calculating the root mean square (RMS) error of the touchdown altitude and reported runway altitude for a large set of flights. The set of parameters that minimize this RMS error are chosen as the final parameters and the touchdown point is evaluated for each flight. The flight data is also smoothed and the runway of landing identified in intermediate steps in this analysis.

The second analysis involves obtaining statistically averaged nominal profiles. For achieving this, each flight is sampled based on the distance remaining to the runway threshold. The nominal profile is then obtained by averaging the altitude and velocity across a large database of flight records at small intervals of distance from the runway threshold. Along with a simple average, weighted averages are also explored in this part.

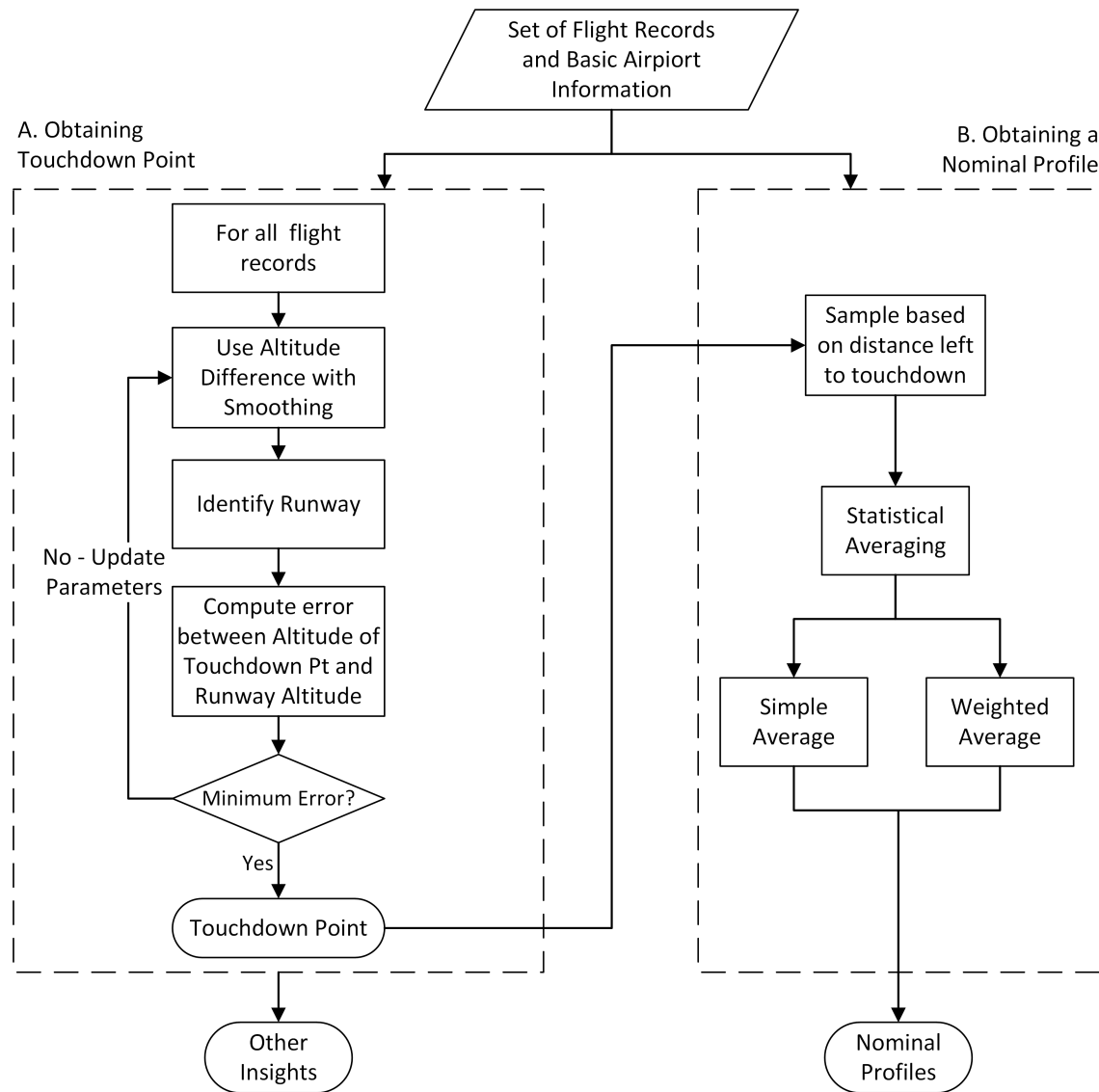


Figure 1. Broad overview of the methodology

III. Implementation and Results

In this study a large set of flight data records (more than 800) from training flights on Cessna 172S aircraft is utilized. One of the first steps taken to analyze the data was to parse the raw data from the recorders. The flight data obtained contained a lot of noise and smoothing the data was essential to allow exploration of trends using this data. In their research on identification of phases of flight for GA operations Goblet et al.¹³ have explored various techniques for smoothing the data. While their figures of merit are based on identifying the phases of flight for the whole data record, our application focuses on the touchdown point. However, the recommendations from their work are considered while choosing the appropriate smoothing

technique. The following subsection contains details of the first part of the methodology.

A. Obtaining Touchdown Point

The flight data is smoothed using a local regression with weighted linear least squares in MATLAB (called “loess” smoothing). Details of the implementation can be found in the MATLAB documentation.¹⁴ Obtaining the touchdown point accurately requires two parameters to be tuned. The span or window of smoothing (hereafter called smoothing parameter) is one of the parameters used to reduce RMS error. The touchdown point for the current work is defined as the last point in the final approach beyond which the altitude difference between successive smoothed data points do not exceed a certain threshold (example one foot). This altitude threshold is the other parameter under our control to reduce the RMS error.

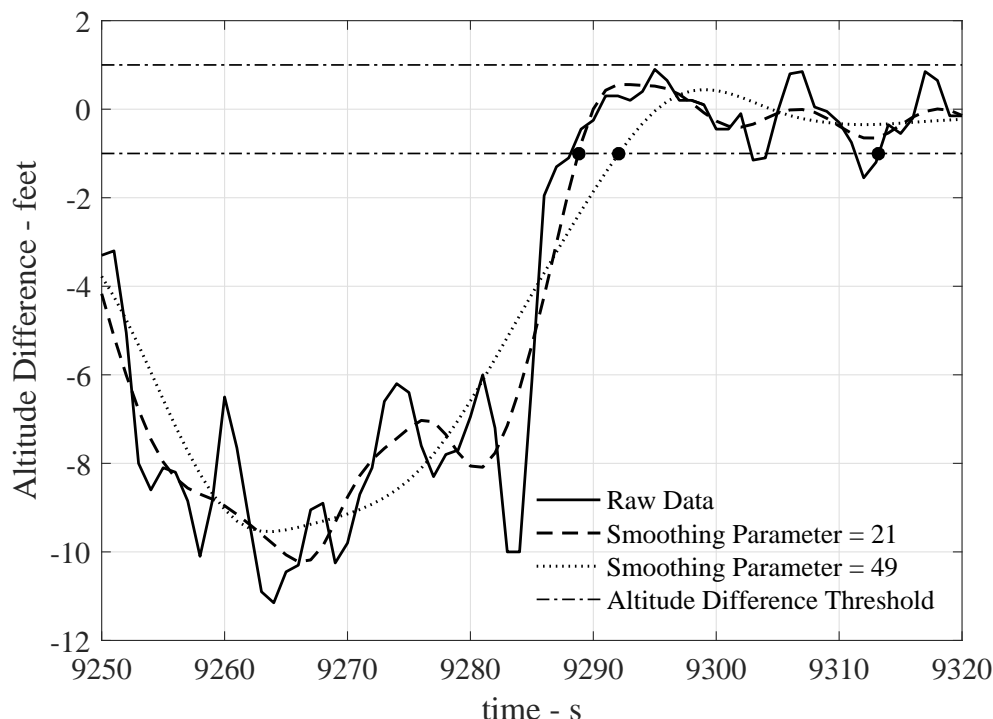


Figure 2. Comparison of different smoothing parameters and their effect on identification of touchdown point

Vertical speed or altitude difference can both be used as the threshold parameter. The reason for using the altitude difference as opposed to the vertical speed was the noisiness of the vertical speed data. Figure 2 shows the effect of the two tuning parameters on the touchdown point identification algorithm. The horizontal dashed lines represent the altitude threshold parameter. This parameter is used to specify the rule for maximum altitude difference permissible between successive points after the aircraft has touched down. The higher the value of the parameter, the wider is the gap between the two horizontal lines, which would imply detection of touchdown point possibly earlier than the actual touchdown. If the value is too small, then the touchdown point would be detected too late (or not detected at all due to the noise in the data). Therefore, it is important to choose this parameter carefully. In the current work, this parameter is chosen as 1 ft based on an analysis described later in the section.

For the smoothing parameter, the solid line plots the altitude difference from the raw data collected from the flights. The altitude difference between successive points in the raw data does not strictly go to zero even after the aircraft has touched down on the runway. In some cases, the magnitude of the noise is as high as 7 feet even after the aircraft has landed. Formulating a general rule for hundreds of data records that may contain this kind of noise proves to be difficult and error-prone. Therefore, smoothing using local regression is utilized. The dashed and dotted curves shown in the Figure 2 indicate the effect of changing the smoothing parameter (the smoothing window) from 21 to 39. Increasing the smoothing parameter uses a larger window for smoothing and thereby some of the features are lost. On the other hand, a smaller

smoothing parameter does not smooth the raw data sufficiently and may retain some of the noise that we want to eliminate from the original data. Therefore, this factor also plays an important role in implementing a robust strategy that can be used over a large set of flight records without tuning it separately for each flight record.

As seen in Figure 2, the touchdown points identified using the raw data and the different smoothing parameters with an altitude threshold of one foot are highlighted as black circular markers. It is quite clear that using the noisy raw data can lead to erroneous touchdown point identification as illustrated in the figure. Smoothing the data can prevent this error, but excessive smoothing might result in a touchdown point identification after the actual touchdown (Smoothing Parameter 21 versus 49 in the figure).

From a set of N flight data records, if the altitude of runway touchdown for flight number i is h_i and the corresponding runway altitude is $h_{r,i}$, then the touchdown altitude error for flight i is:

$$e_i = h_i - h_{r,i} \quad (1)$$

Using the error for each individual record, the total RMS error is given by Equation 2

$$RMS = \sqrt{\frac{\sum_{n=1}^N e_i^2}{N}} \quad (2)$$

To observe the effects of each parameter and to aid in the appropriate selection of particular values for each parameter, an experiment is performed in which each parameter is varied between certain lower and upper bounds and the RMS error is calculated.

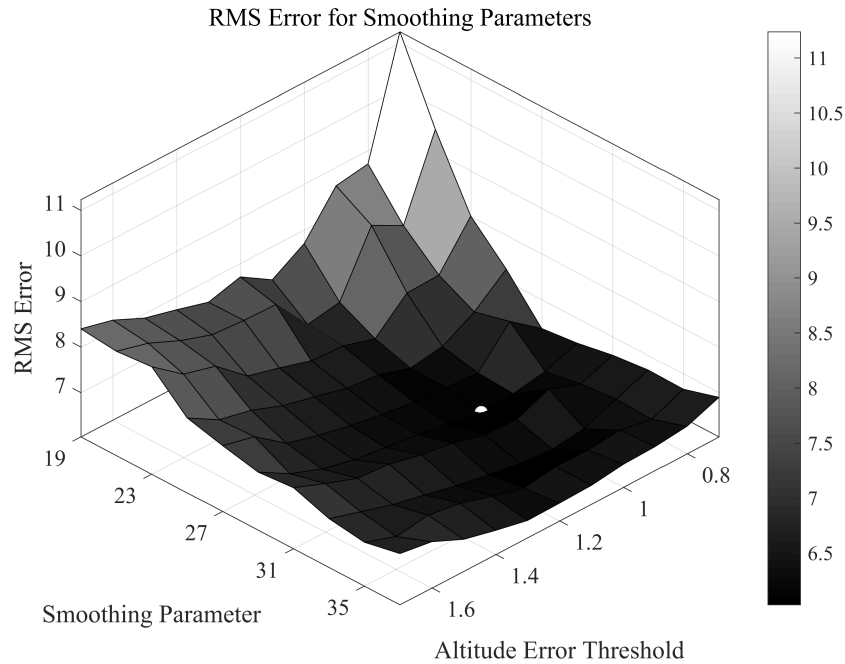


Figure 3. 3-D Surface plot of the RMS error for different smoothing parameters and thresholds

Setting the upper bound of the smoothing parameter too large would smooth the data too much resulting in lower RMS error but result in touchdown points that are further along the ground roll than at actual touchdown. This experiment is performed for a large set of flight records, and the results are shown in Figure 3.

Figure 3 shows the trend of the RMS error on the z -axis with the two parameters on the x and y -axis. As we can see from the figure, low values of smoothing parameters generally result in higher errors as expected.

This goes down as the smoothing is increased. Also, lower values of altitude threshold also tend to increase the RMS error. High values of altitude threshold may result in premature detection of touchdown point resulting in higher individual errors for each record. The chosen point (highlighted in the figure with a white dot), results in the smallest RMS error. This point corresponds to a parameter pair of altitude threshold = 1 and smoothing parameter = 27. For the selected parameters, a histogram of altitude error is then plotted as seen in Figure 4a. As we can see, for most of the flight records, the altitude of touchdown point is within ± 5 feet of the runway altitude.

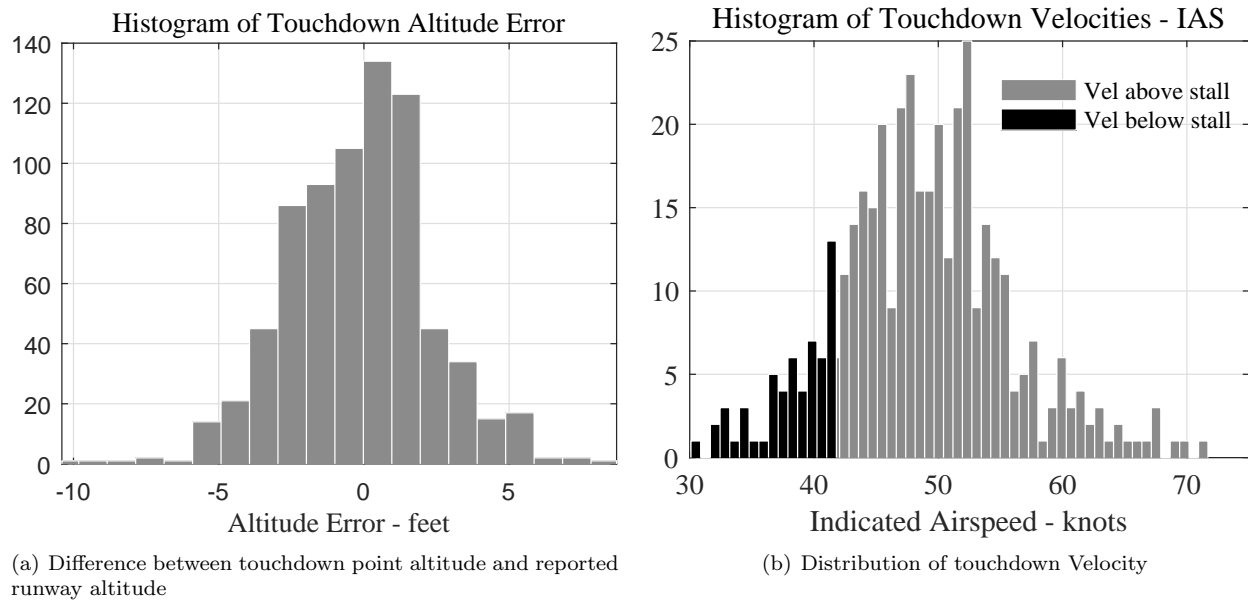


Figure 4. Altitude error and touchdown velocity distributions

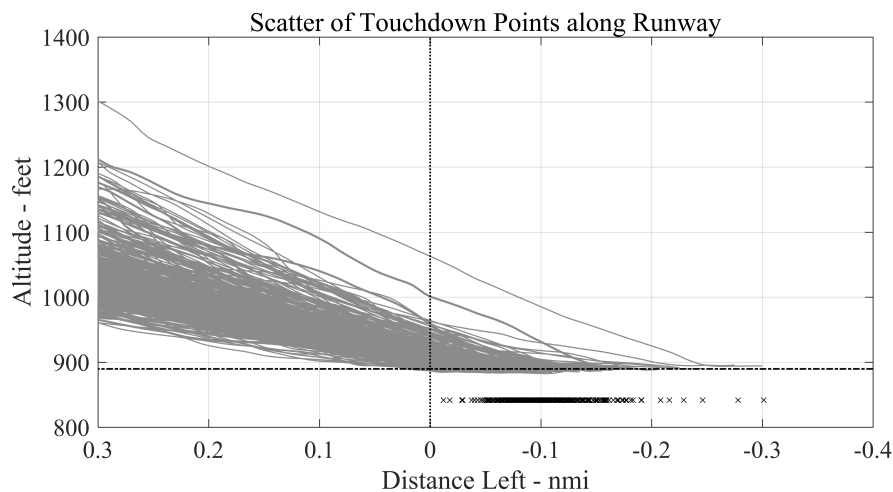


Figure 5. Scatter of approach and landing with identified touchdown points

Along with the altitude error, it is also important to gain additional insights into the approach and landings of these flight records. One such insight is the distribution of the touchdown velocity. Figure 4b shows the distribution of touchdown velocities for all the flight records considered. The darker bars represent those touchdowns that occurred at or below the stall velocity at that altitude as reported by the Pilot Operating Handbook for the Cessna 172.¹⁵ It can be seen that a small percentage of the flights touch down at or below stall velocity. This can be due to several reasons enumerated below:

1. This stall velocity is calculated at max gross weight and corrected for altitude. Some of the stalled touchdowns can be due to the considerably lower landing weight of each flight which will shift the stall velocity lower
2. The algorithm detects the touchdown point slightly after the actual touchdown in which case the velocity would have decreased
3. Since these records are from instructional flights where pilots might be instructed to hold the aircraft off the ground during the landing flare until the stall warning had been heard
4. Aircraft in ground effect might affect the stall velocity

There could be other reasons for this trend that have not yet been uncovered. If the number of records that have touchdown velocities below stall would have been significantly higher, it would have prompted going back to the original algorithm and tightening the upper bound of the smoothing parameter. However, the overall trend is captured sufficiently which lends confidence to the earlier selection of parameters. Another way to visualize these results is to plot the trace of the approach and landing along with the touchdown point as a function of distance remaining. This can be seen in Figure 5, where the “×” symbol represents the location along the runway where the flight touched down. These kind of insights and visualizations are important when using this framework assess GA operation safety.

B. Obtaining a Nominal Approach Profile

Once the touchdown point is obtained for all the flight data records, they are sampled according to the distance left to the touchdown point. Using the information that is visualized in Figure 5, the distance of the touchdown point from the runway threshold can also be evaluated. It is important to discretize/sample the flights as a function of distance as this allows the generation of a statistical average (nominal) profile.

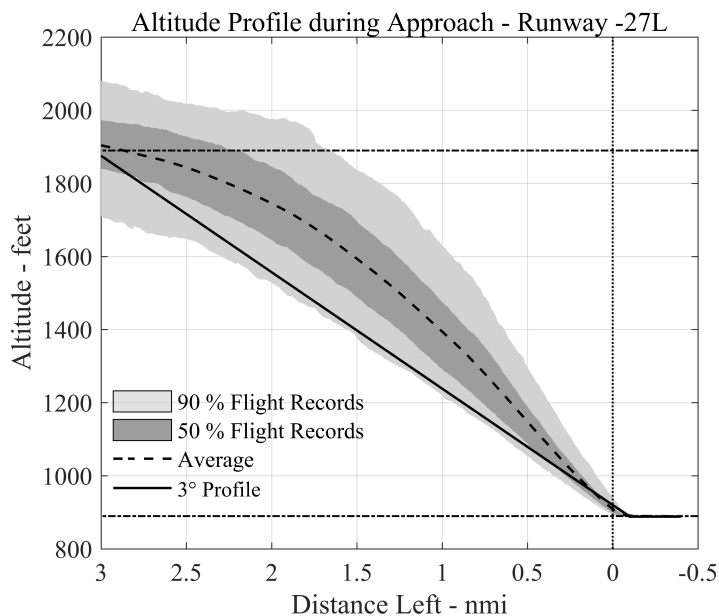


Figure 6. Nominal approach profile - Altitude

The segment leading up to the touchdown point is obtained by using a spline interpolation of available data points at a discretization of 0.001 nautical miles. This facilitates efficient visualization of altitude (and other parameters) for each flight when it was a certain distance away from the runway threshold. This also allows for comparison of different flights landing on each runway.

Figure 6 shows this approach and landing data visualized for a representative runway - 27L. This data set contains more than 400 landings on this runway and therefore it represents a good candidate for carrying out a statistical study. In Figure 6, a reference 3° glide slope line (common practice for approach operations)

from the “aim point” on the runway is shown by the solid black line. The dotted line shows the altitude profile followed by all the flights landing on this runway “on an average”. The shaded regions show the spread of the flight data records, with the dark grey denoting the 50th percentile and the light grey denoting the 90th percentile of data records. The dotted vertical line is the runway threshold and the horizontal line at approx 1900 feet represents the 1000 feet above ground level marker for this runway.

It can be seen that most of the flight records tend to intercept a 3° glide slope approximately thousand feet above the airport/runway altitude (horizontal dashed line). This also corresponds to being approximately 3 nautical miles out from the runway threshold. The average approach profile and most of the individual records tend to fly above the reference 3° glide slope line. But we can also see that there is much variation in the altitude profile of different flights as they approach and land at this runway. While some variation is expected, it is interesting to note that almost all (90th percentile) of the flights tend to fly above the 3° glide slope. This results in the spread of the touchdown points seen earlier in Figure 5. Therefore, we can conclude that in GA operations, the altitude profile followed during approach and landing is not a simple linear 3° slope line. These insights will be useful when applying or using these nominal profiles in other applications such as safety analysis.

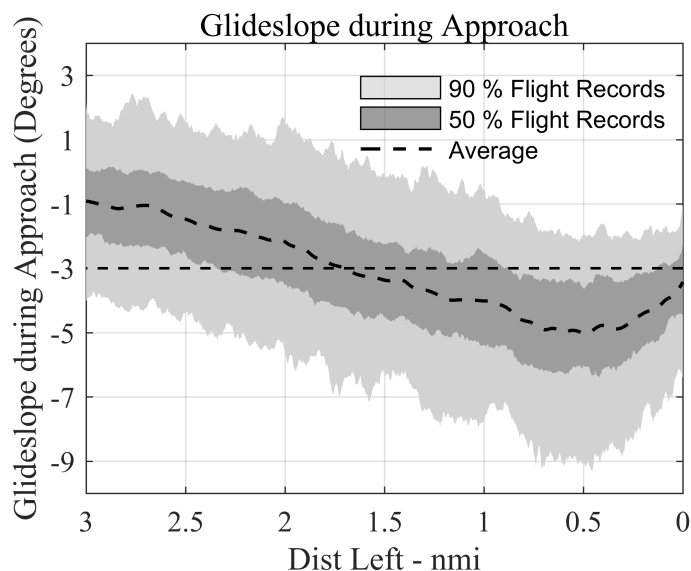


Figure 7. Nominal glide slope during approach

At this point, it is also worthwhile to look at the actual instantaneous glide slope ($\frac{dh}{dx}$) followed by different flights, along with the corresponding average and the spread. These data are shown in Figure 7. From this figure, it is clear that most of the flights (and the average) tend to have a shallower than 3° glide slope when they are at 1000 feet above ground level. This slope gradually becomes steeper and most of the flights tend to have a steeper than 3° slope when they land. Thus it is evident that, during actual GA operations, there is a lot of variability in the actual glide slope of the aircraft.

Therefore, the data presented here clearly indicates that during actual operations, defining a “reference” trajectory as simply along a 3° glide slope to the touchdown point would be an oversimplification of the actual process. For this reason, it is proposed to use or define the statistical average profile developed here as the nominal profile from an operational perspective.

Having already defined a nominal altitude profile, a similar approach can be taken to look at the velocity profile. We have already seen in the introduction section how the velocity profile for approach and landing is defined for commercial aircraft. Using the same set of flight records and the same technique of discretization and sampling, an average statistical profile for the velocity is obtained in Figure 8. In this figure, the horizontal line at 110 knots represents the “no flaps speed” for the current aircraft (obtained from Pilot Operating Handbook).¹⁵ The dotted line is the average and the shaded regions represent the 50 percentile and 90 percentile of the spread. Although there is no crisp reference to compare against such as the 3° profile for altitude, it is again evident that there is a significant drop in the velocity from the time of interception of the 1000 feet above ground level (AGL) line to the actual touchdown. The velocity profile

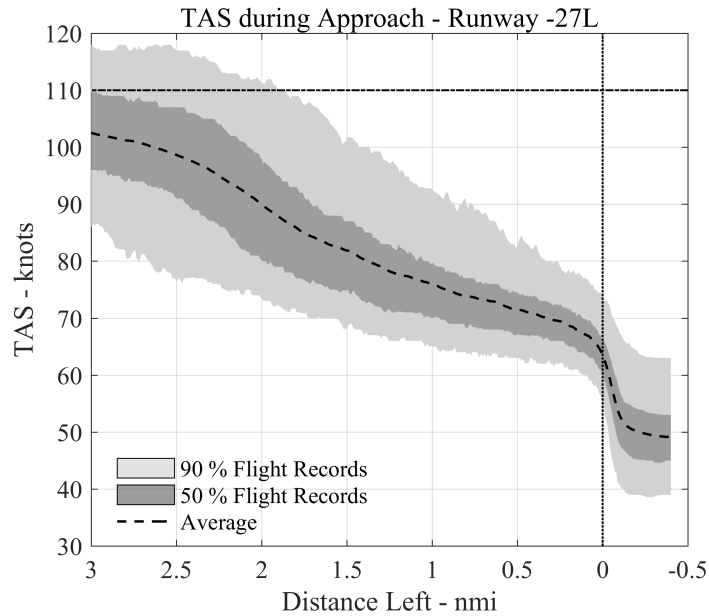


Figure 8. Nominal approach profile - Velocity

during approach indicates that the average velocity profile drops from around 100 knots to 60 knots from the point of interception of 1000 feet AGL line to the runway threshold. Also, there are no noticeable steps in the velocity profile suggesting against a stepped approach.

Once the nominal profiles for altitude and velocity were obtained, these are then extended beyond the 3 nautical mile distance to further distances to visualize and understand them better. This extension (upto 6 nautical miles distance remaining) can be seen in Figure 9a and 9b. From the altitude profile it can be seen that beyond 3 nautical miles, the spread of flight data records increases quite a bit. This can be attributed to touch-and-go maneuvers that might be executed by the aircraft. Therefore, this nominal or average profile that is being defined only makes sense upto this point. Similar spread can be seen in the velocity profiles.

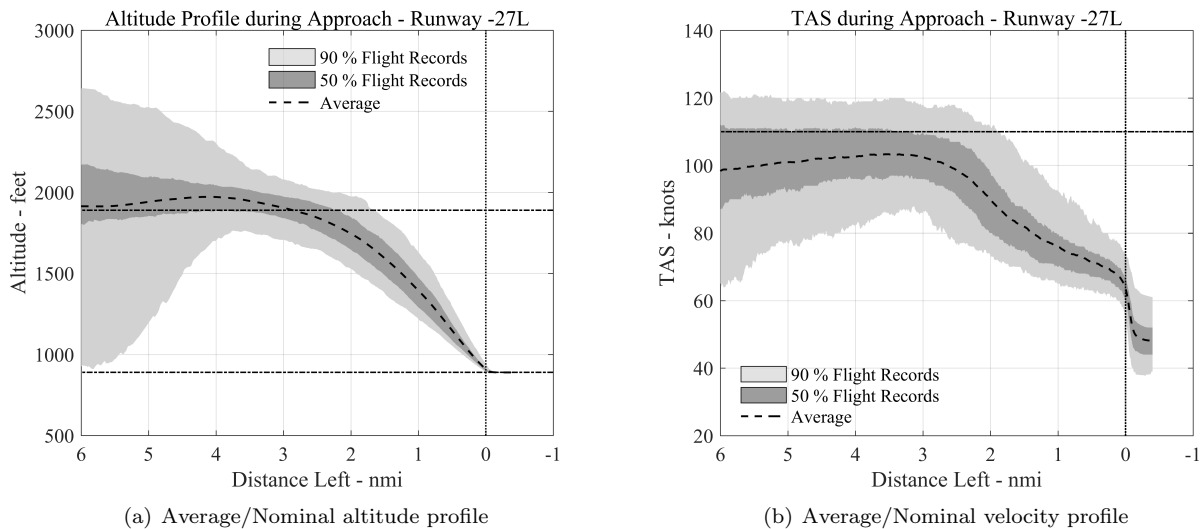


Figure 9. Visualization of average profiles beyond 3 nautical miles

All the above inferences were purely based on the statistical data of the flight records in use and are therefore more of “operational” cut-offs. But they are very useful in achieving the purpose of defining

the nominal approach profiles. Before talking about different types of reference profiles in the following subsection, it is worth noting that like altitude and velocity, these nominal profiles are obtained for other parameters as well such as pitch, roll, RPM etc. For the sake of brevity, only altitude and velocity are presented.

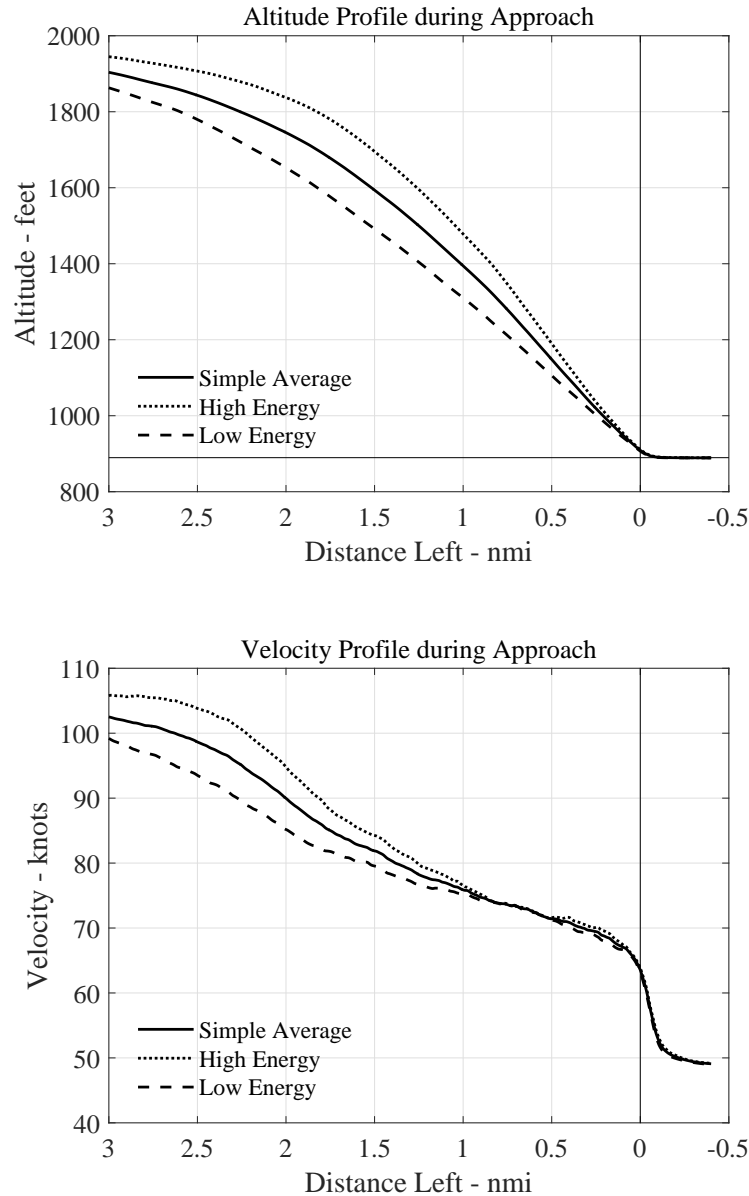


Figure 10. Different reference profiles - total energy weighted

C. Different Types of Nominal Profiles

Once the nominal profiles are obtained using simple averaging of the data from the flight records, further types of nominal profiles were developed. One of the possible types of profile of interest is energy-weighted profile. An implementation of this can be seen in Figure 10. For each flight record, the average value of specific potential energy, specific kinetic energy and specific total energy are calculated from the flight data. Different weighted profiles of altitude and true airspeed are generated using high-energy and low-energy profiles. As seen in Figure 10, the solid line represents the simple average profile obtained earlier, the dashed line is the profile obtained by giving higher weighting to low-energy profiles and the dotted line obtained

using higher weighting for high-energy profiles.

An interesting trend is evident from the figure: while there is a significant difference between the reference altitude profiles of high and low-energy approaches, the velocity profiles seem to merge around the one nautical mile left area. This suggests that approaches that have a high or low value of specific total energy during final stages of approach tend to have this mainly due to the difference between altitude profiles.

A similar exercise is carried out, but now with the weightings based on the specific kinetic energy rather than specific total energy. This can be seen in Figure 11. It is observed that on an average, the approaches that have a high or low kinetic energy tend to have more or less the same average altitude profile. Therefore, having a high or low kinetic energy does not necessarily imply a lot of variation in the average altitude profile.

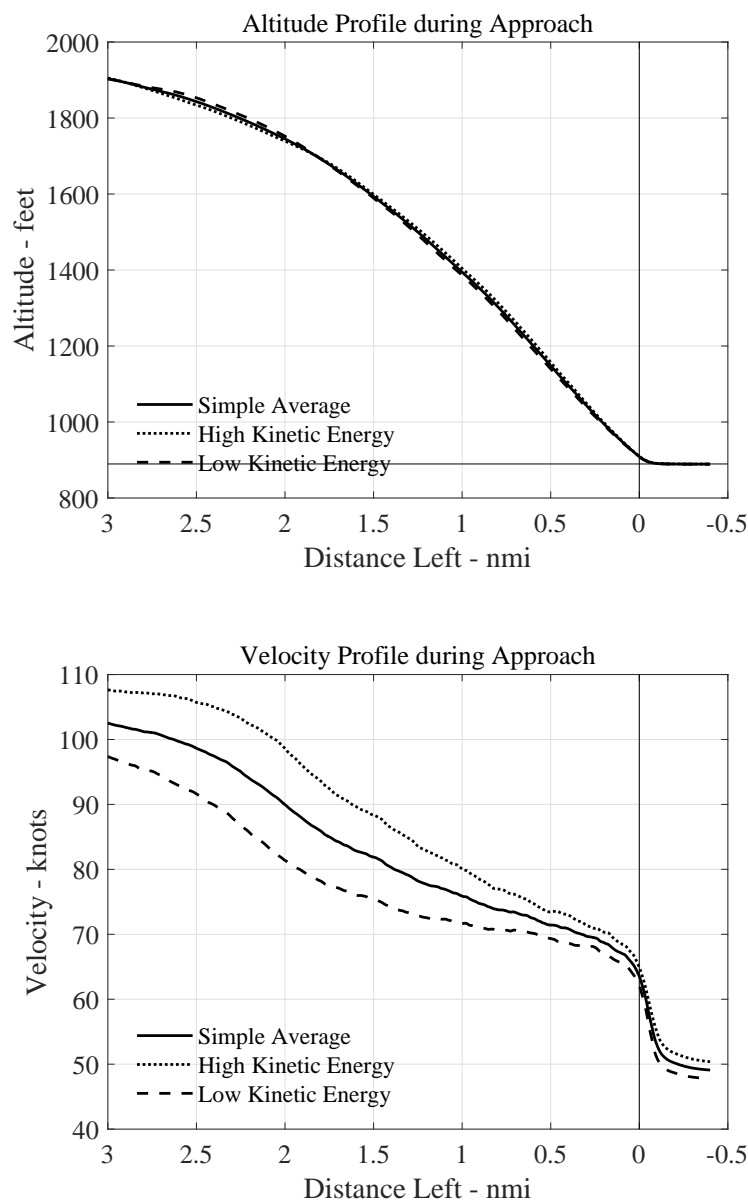


Figure 11. Different reference profiles - kinetic energy weighted

When the same experiment is carried out with weightings based on specific potential energy rather than specific kinetic energy, a similar observation can be made. The trends from Figure 12 show that high or low potential energy approaches tend to have more or less the same average velocity profile.

All the above experiments lead to insights on approach and landing operations for GA aircraft which

would otherwise have not been obvious by looking at the flight data alone. Other types of nominal profiles may be obtained using various rules for weighting different flight records.

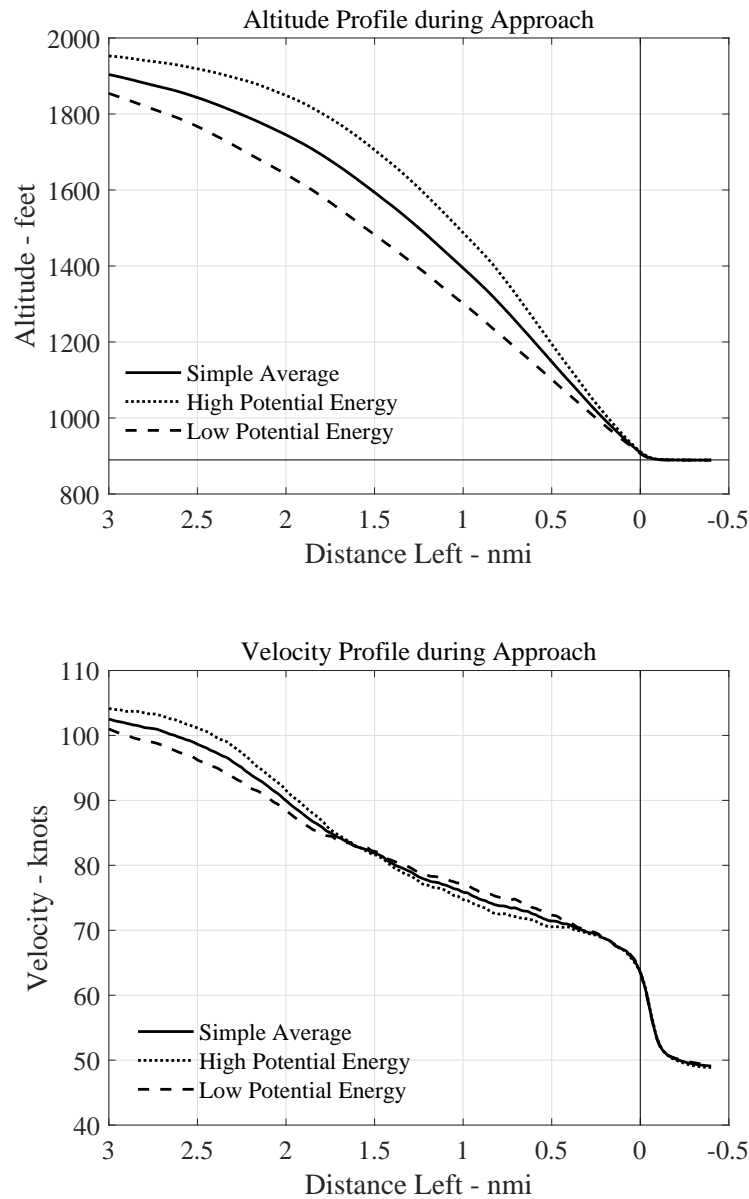


Figure 12. Different reference profiles - potential energy weighted

IV. Conclusions

In this paper we have demonstrated the implementation and visualization of a nominal or reference approach profile for GA operations. We have laid out a methodology for obtaining the touchdown point using a set of flight data records and smoothing algorithms. Once this is achieved, the flight records are sampled based on distance remaining, rather than time, in order to compare hundreds of records with each other. This facilitated the statistical averaging of the flight records to obtain nominal profiles of altitude and velocity during approach and landing. We also demonstrate using energy-weighted averaging to obtain different types of nominal profiles which provide insights into the energy-state of the aircraft during approach and landing.

Because of the lack of clear definition on this topic in GA, it was important to identify a way of defining

these nominal profiles. Once these nominal profiles have been identified, they can be used to assess and augment efforts to enhance safety of GA operations.

Acknowledgments

This work was sponsored by the Federal Aviation Administration under Project No. 5 of the FAA Center of Excellence for General Aviation, PEGASAS (Partnership to Enhance General Aviation Safety Accessibility and Sustainability), via grant No. 12-C-GA-GIT-004 to the Georgia Institute of Technology. The authors are grateful to FAA project technical monitor Mr. Michael Vu, and to project partners at Purdue University and The Ohio State University. The information in this research does not constitute FAA Flight Standards or FAA Aircraft Certification policy. The authors would also like to thank Dr. Imon Chakraborty of the Aerospace Systems Design Lab for his valuable feedback and comments.

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